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THERMAL PERFORMANCE AND CHARACTERISTICS OF SPIRAL-TUBE GROUND HEAT EXCHANGER FOR GROUND-SOURCE HEAT PUMP

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ABSTRACT

This study investigates thermal performance and characteristics of spiral-tube ground heat exchanger (GHE) for ground source heat pump in laminar and turbulent flows. The thermal performances are evaluated by numerical method using a CFD code. Various models of spiral-tube GHEs installed in a borehole and backfilled with silica-sand were simulated. In comparison with the conventional U-tube GHE, the performance of spiral-tube GHE increases by 62.7 % in the laminar flow and by 33.5 % in the turbulent flow. Due to the interest in applying the GHE in concrete foundation piles, the spiral-tube GHE installed in a concrete pile is also simulated. Its performance shows a slight better performance of 5 % in the laminar flow and 6 % in the turbulent flow compared with that of a borehole backfilled with silica sand. Furthermore, the performance of spiral-tube GHEs with outlet pipe installed inside and outside the spiral tube in the borehole, and varying spiral pitches of p = 0.05 m; 0.1 m and 0.2 m are investigated. The effects of outlet pipe positions on the performances are shown. The spiral-tube with outlet pipe installed outside gives a better performance, of 2 % in the laminar flow and 10 % in the turbulent flow, than that of the outlet pipe installed inside. Water temperature distributions of the both spiral-tube GHEs are presented. Varying the spiral pitch significantly affects the performance of the spiral-tube GHEs. Increasing the spiral pitch reduces the number of spirals per meter borehole depth.

KEY WORDS: Geothermal energy, Heat exchanger, Computational methods, Spiral-tube GHE, Thermal performance

1. INTRODUCTION

The geothermal energy source is categorized based on ASHRAE [1] for use in high-temperature electric power production; > 150 ^{o}C (423 K), intermediate and low–temperature direct-use applications; < 150 ^{o}C (423 K), and Ground-source heat pump (GSHP) system applications; generally < 32 ^{o}C (305 K). The GSHP system has been widely used in engineering application for space heating and cooling. Ground heat exchanger (GHE) is used in the ground-source heat pump to exchange heat with the ground. The GSHP technology with the various models and design/simulation techniques was described in a detailed review of models and systems of vertical GSHPs [2]. Several types of GHEs have been studied for different flow rates and different operation modes. Operating the GHEs with various conditions shows the different characteristic in their heat exchange rates [3-7]. An energy pile system was studied in order to reduce the initial cost of the GHE. The performances of several types of GHEs applied to the pile foundations in actual buildings were studied by Hammada et al. [8]. Gao et al. [9] also studied several types of vertical pile-foundation heat exchangers. Recently, a spiral-tube GHE is investigated to study its performance. In the spiral-tube GHE, spiral-pipe is installed in the borehole or concrete pile. Several explicit exact solutions for heat conduction in anisotropic infinite or semi-infinite media applied to borehole ground heat exchangers and energy piles (or pile ground heat exchangers) have been developed by Li and Lai [10].

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Analytical solutions of spiral coil ground heat exchangers have been developed. The classical approaches, i.e. the line heat source model and the “hollow” cylindrical heat source model, are no longer valid for thermal analysis and design of the GHE with spiral coils in foundation pile. A “solid” cylindrical source model has been developed considering the radial dimension and the heat capacity of the borehole or pile [11]. Cui et al. [12] developed the ring-coil source model taking into account the discontinuity of the heat source and the impact of the coil pitches. However, this model does not simulate the heat transfer of fluid circulating inside the spiral coil pipe. A spiral heat source model has been developed for better thermal analysis [13]. Thermal behaviour of a conventional double-U-tube and a helical-shaped pipe for long and short term operation was analyzed by Zarrella et al. [14]. The thermal performance of the helical-shaped pipe was better than the double U-tube heat exchanger.

Knowledge of the performance of the spiral-tube GHE in various conditions is crucial to apply it in application. This work investigated the performance of spiral-tube GHEs in various conditions. Comparison with the conventional U-tube GHE was also carried out. In the spiral-tube GHE, a spiral pipe is installed in the borehole backfilled with silica sand and in the concrete pile. Various conditions include spiral pitches of p = 0.05 m; 0.1 m and 0.2 m and outlet pipe positions. The GHE performances are analyzed in the laminar and turbulent flows.

2. GROUND HEAT EXCHANGER

The schematic diagrams of the conventional U-tube and spiral tube GHEs are shown in Fig. 1. Polyethylene pipes were used as the tubes of the GHEs. Steel pipes, which are used as foundation pile for houses, were buried in the ground at a depth of 20 m and used as boreholes for the GHEs. The GHEs were inserted in the steel pile, and the gaps between the steel pile and tubes were backfilled with silica-sand. In the spiral tube GHE, a spiral pipe is used as the inlet tube of the GHE and a straight pipe is used as the outlet tube. In addition, the spiral tube was also installed using concrete pile foundation as shown in Fig. 1(b). The spiral-tube with outlet pipe installed outside is shown in Fig. 1(c).

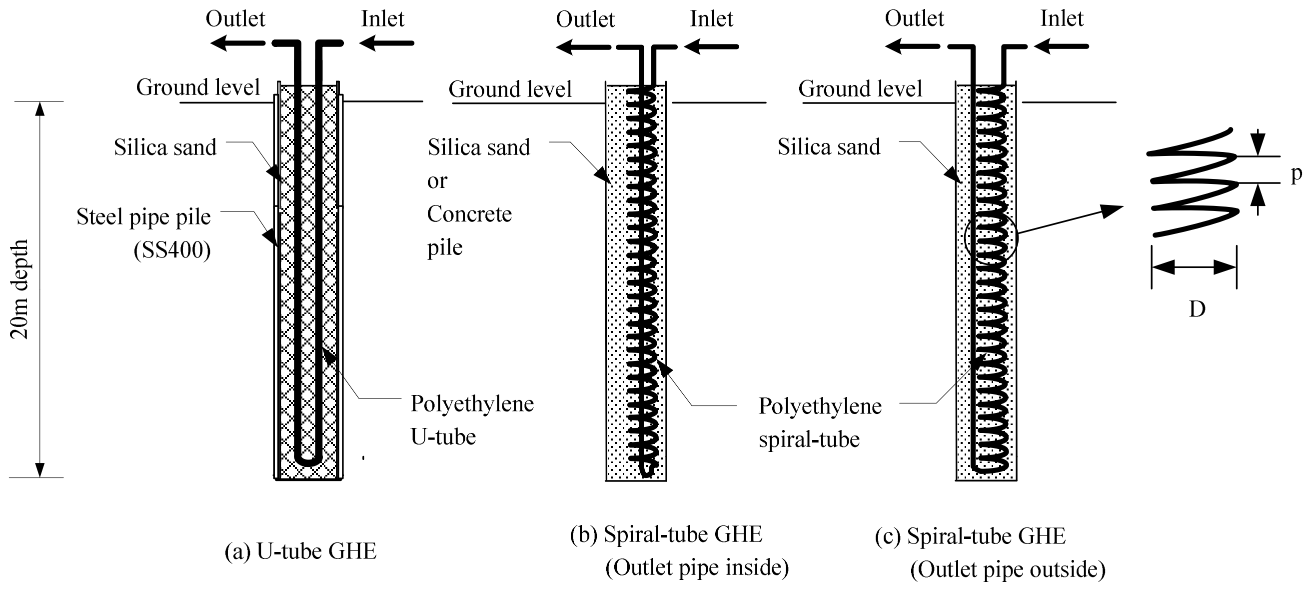


Fig. 1 The schematic diagrams of the U-tube and Spiral-tube GHEs

3. SIMULATION SET-UP

3.1 Three-Dimensional Models of the GHEs

Three-dimensional unsteady models were built and simulated using the CFD-code, FLUENT, in order to investigate heat exchange from the GHEs' system to the ground around the borehole. The software uses a finite volume method to convert the governing equations to numerically solvable algebraic equations. Fig. 2 shows the three-dimensional model of the conventional U-tube and spiral-tube GHEs. Spiral pitches for the spiral-tube GHEs with outlet pipe installed inside are p = 0.05 m; 0.1 m and 0.2 m as shown in Fig. 2 (b). Outlet pipe installed outside is shown in Fig. 2(b).

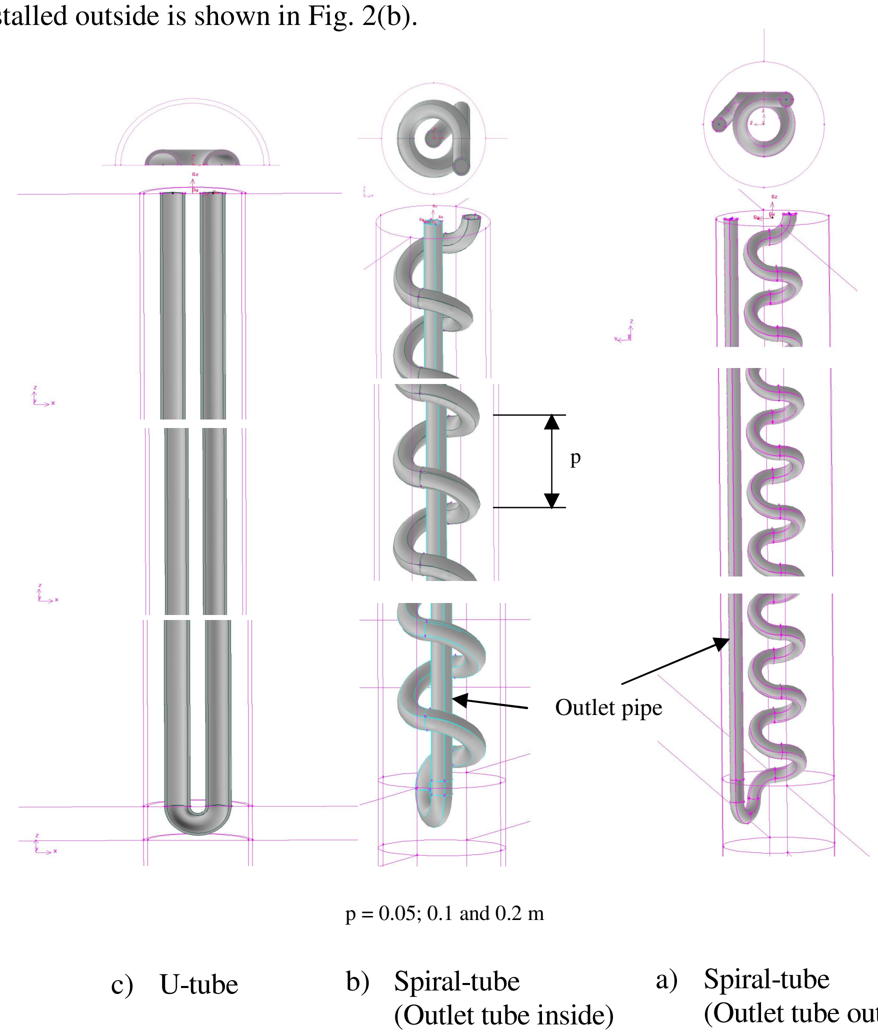


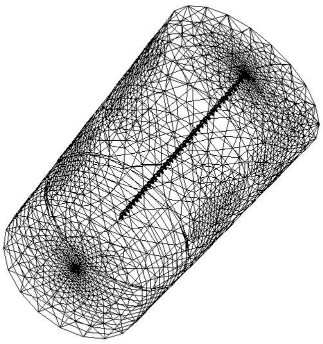
Fig. 2 Three-dimensional model of the conventional U-tube and Spiral-tube GHEs

The ground around the GHEs is modeled up to 5 m in radius. All the related geometric parameters and material thermal properties for the GHEs are listed in Table 1. Inlet and outlet pipes for the both GHEs, U-tube and spiral-tube, are made of Polyethylene pipes. The ground profiles around the borehole consist of Clay and Sandy-clay. Ground profile from ground level to 15 m in depth is Clay and below 15 m is Sandy-clay. The properties of the ground are presented in Table 2.

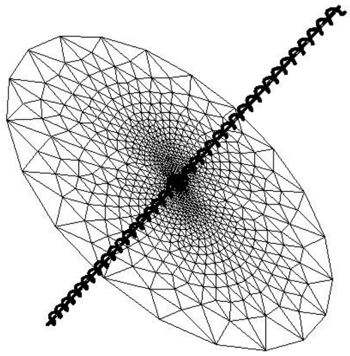
Three-dimensional hybrid mesh generation was applied in the GHE models. The numerical mesh of the borehole and ground for the spiral-tube GHE is shown in Fig. 3. The mid-view shown in Fig. 3 (b) is in the cross-section of 10 m depth of the borehole and ground. Meshing around the borehole is shown in Fig. 3 (d).

Table 1 Geometric parameters and material thermal properties of the GHEs

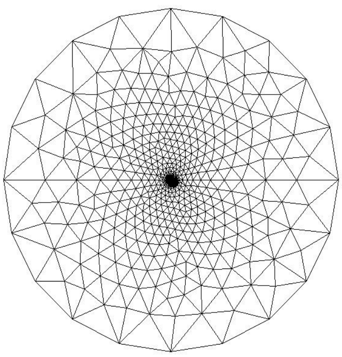
Parameters	Value	Unit
Inlet and outlet pipes of the GHEs, U-pipe and Spiral-pipe (material: Polyethylene)		
Outer diameter, d_o	0.033	m
Inner diameter, d_i	0.026	m
Thermal conductivity, k_{PE}	0.35	W/(m K)
Specific heat, c_P	2300	J/kg K
Density, ρ	920	kg/m^3
Leg spacing for U-Tube GHE, x	0.02	m
Pitch for Spiral-tube GHEs, p	0.05; 0.1 and 0.2	m
Grout (material: Silica sand)		
Thermal conductivity, k_{grout}	1.4	W/(m K)
Specific heat, c_P	750	J/kg K
Density, ρ	2210	kg/m3
Concrete pile		
Density, ρ	2200	kg/m^3
Specific heat, c_P	1000	J/kg.K
Thermal conductivity, $k_{Concrete\text{-}pile}$	1.65	W/m.K



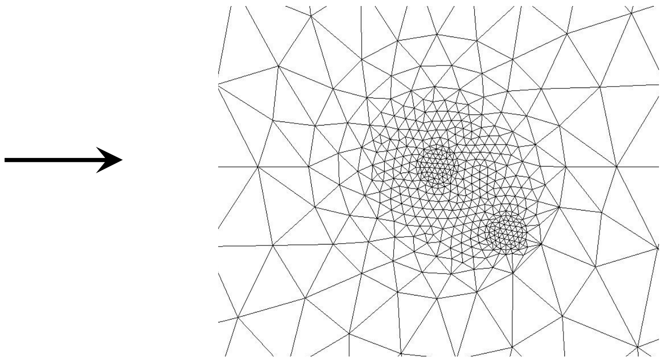
a) Model



b) Mid-view of the Model



c) Top-view of the Model



d) Magnified around the borehole

Fig. 3 Numerical mesh of the borehole and ground of the Spiral-tube GHE model

Table 2 The properties of the ground

Parameters	Value	Unit
Clay (temperature: 293 K; water content: 27.7%)		
Density, ρ	1700	kg/m^3
Specific heat, c_P	1800	J/kg.K
Thermal conductivity, k_{Clay}	1.2	W/m.K
Sandy-clay (temperature: 293 K; water content: 21.6%)		
Density, ρ	1960	kg/m^3
Specific heat, c_P	1200	J/kg.K
Thermal conductivity, $k_{Sandy\text{-}clay}$	2.1	W/m.K

3.2 Boundary and Initial Conditions

A constant and uniform temperature was applied to the top and bottom surfaces of the model. Variation of ground temperature near the surface due to ambient climate effect is negligible. Initial ground temperature is assumed to be constant at 17.7 °C. The flow rate of circulated water was set to 2 l/min for laminar flow and 8 l/min for turbulent flow. The GHEs models were simulated in 24 h operation and inlet water temperature was set to be constant of 27 °C. For turbulence model, k-epsilon two equation models were applied in the FLUENT simulation set-up. Scaled residuals for turbulence models were monitored. Turbulence specification method is use turbulence intensity, $I=0.16(Re_{DH})^{-1/8}$.

3.3 Model Validation

The grid for U-tube GHE was generated using gambit to perform grid independence test. The GHEs were simulated in 24 h continuous operation and its heat exchange rate was investigated. The cell number of the Grid is shown in Table 3. The heat exchange rate of the grid 2 in which the total cell number of 197581 for U-tube shows the same results as the finest grid 3 and 4 as shown in Fig. 4. Then, the grid 2 was applied in the model.

The comparison of simulation result of the heat exchange rate of the GHE models with experimental result shows the reasonable agreement. Small differences between the numerical and experimental were caused by discrepancies of several uncertain factors such as local ground thermal properties, boundary and initial conditions, etc. The deviation of heat exchange rate between the experimental and simulated results is in the range of 2-18 % for U-tube.

Table 3 The cell number of the Grid

GHE type	Grid 1	Grid 2	Grid 3	Grid 4
U-tube	46446	197581	438346	388681

A similar hybrid mesh is also applied in the spiral-tube GHE for each component. The heat exchange rates of the spiral tube models were simulated using FLUENT in different time step size as shown in Fig. 5.

3.4 Heat Exchange Rate

The thermal performances of the GHEs were investigated by calculating their heat exchange rates through the water flow. The heat exchange rate is calculated by the following equation

$$Q = \dot{m} c_p \Delta T \tag{1}$$

where $\dot{m}$ is flow rate, c_p is specific heat, and ΔT is the temperature difference between the inlet and outlet tubes of circulated water.

The heat exchange rate per unit length of borehole depth is defined as the following equation and it is used to express the performance of each GHEs.

$$\overline{Q} = Q / L \tag{2}$$

where L is the depth of each GHE.

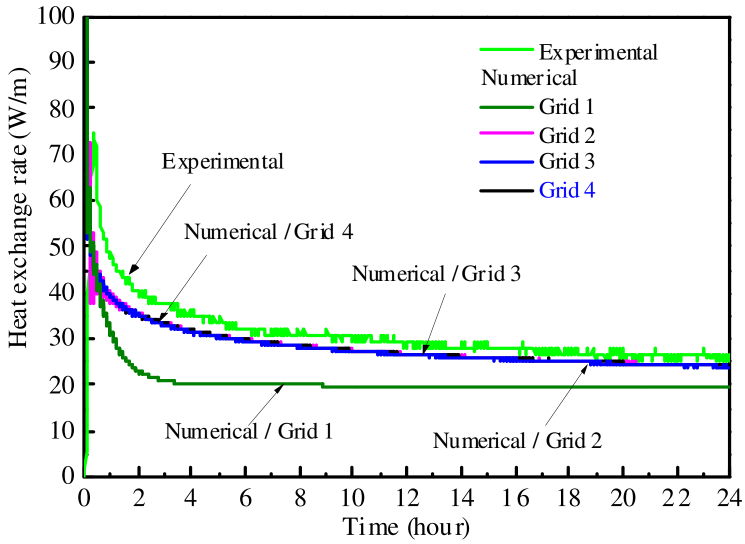


Fig. 4 Heat exchange rates of the U-tube GHE experimentally and numerically

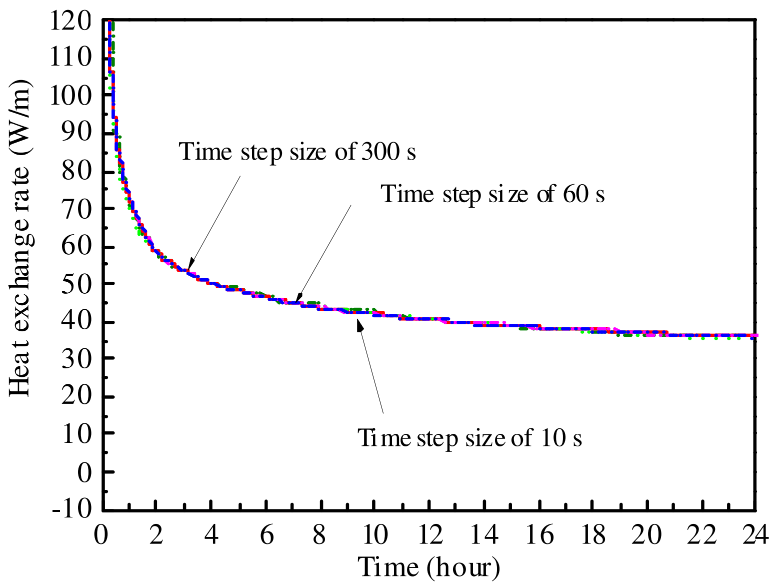


Fig. 5 Heat exchange rate of the U-tube GHE experimentally and numerically

4. RESULTS AND DISCUSSIONS

4.1 Comparison between U-Tube and Spiral-Tube GHEs

The models of the U-tube and spiral tube GHEs with borehole backfilled with silica sand were simulated in the laminar and turbulent flows. Water temperature distribution and heat exchange rate can be shown from the simulation results.

4.1.1 Water temperature distributions

Water temperature distributions of the conventional U-tube and spiral tube GHEs, after 24h operation, are shown in Fig. 6. The temperature of the water is obtained at the centre of the tube for all cases. The water temperature decreases in the flow direction due to heat, with the exception of the laminar flow U-tube where the temperature increases slightly in the lower part of the up pipe. The temperature difference between the inlet and outlet decreases with increasing flow rate, as expected. In the U-tube with laminar flow, the temperature reduces very rapidly in the bottom, U, section of the pipe. In the down flow part of the pipe the temperature loss is propagated into the pipe by conduction only, and a thermal boundary layer then exists within the pipe, with the temperature at the pipe wall lower than at the pipe centre, where the displayed temperature is obtained. In the U section the laminar flow is strongly mixed leading to the observed sudden drop in temperature. The greater reduction in temperature in the spiral tube, as compared to that in the U tube, is due to the longer path of the water in the spiral tube.
The relatively smaller change in temperature in the up pipe in the spiral tubes, is because of the thermal interference from the down pipe.

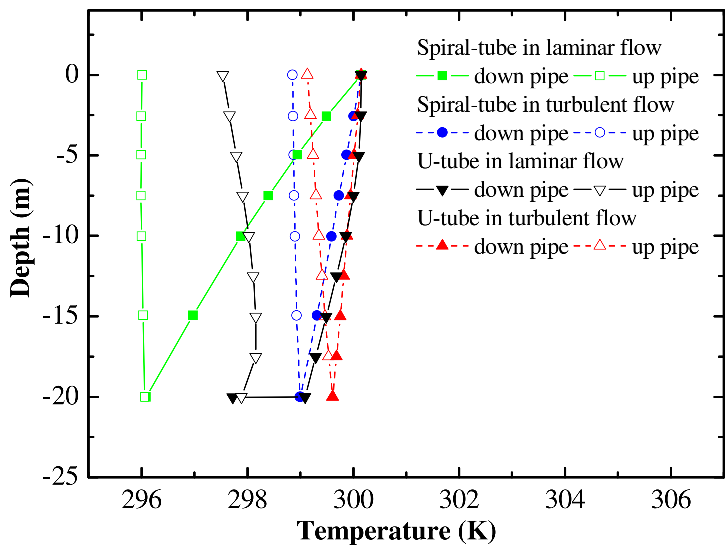


Fig. 6 Water temperature distribution of the GHEs after 24 h operation

4.1.2 Heat Exchange Rates

Fig. 7 shows the heat exchange rates of U-tube and spiral-tube GHEs. Heat exchange rate of the spiral-tube GHE is higher than that of the U-tube GHE. Rejecting heat to the ground is high in the spiral tube due to the long path of the water. This fact indicated that using the spiral tube increases the heat exchange per meter borehole depth, providing the possibility of reducing the borehole depth. The performance of the spiral-tube GHE increases by 62.7 % in the laminar flow and by 33.5 % in the turbulent flow compared with that of the conventional U-tube GHE. Temperature contours of the U-tube and spiral-tube GHEs with borehole backfilled with silica sand in the laminar & turbulent flows are shown in Fig. 8.

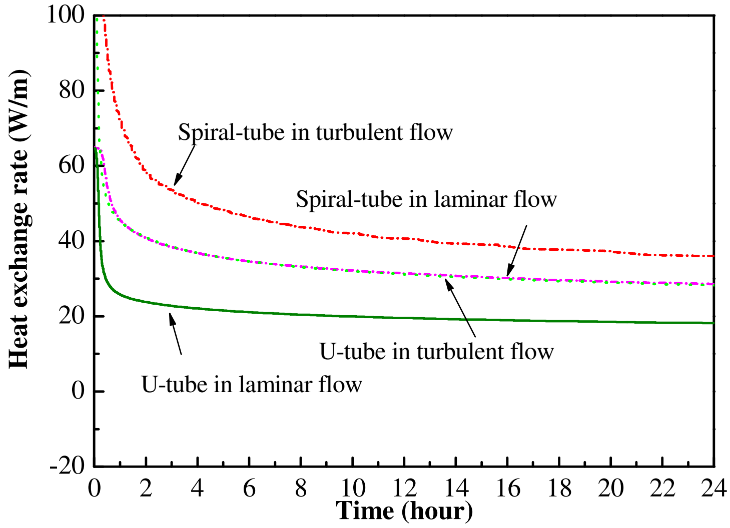


Fig. 7 Heat exchange rates of U-tube and spiral-tube GHEs

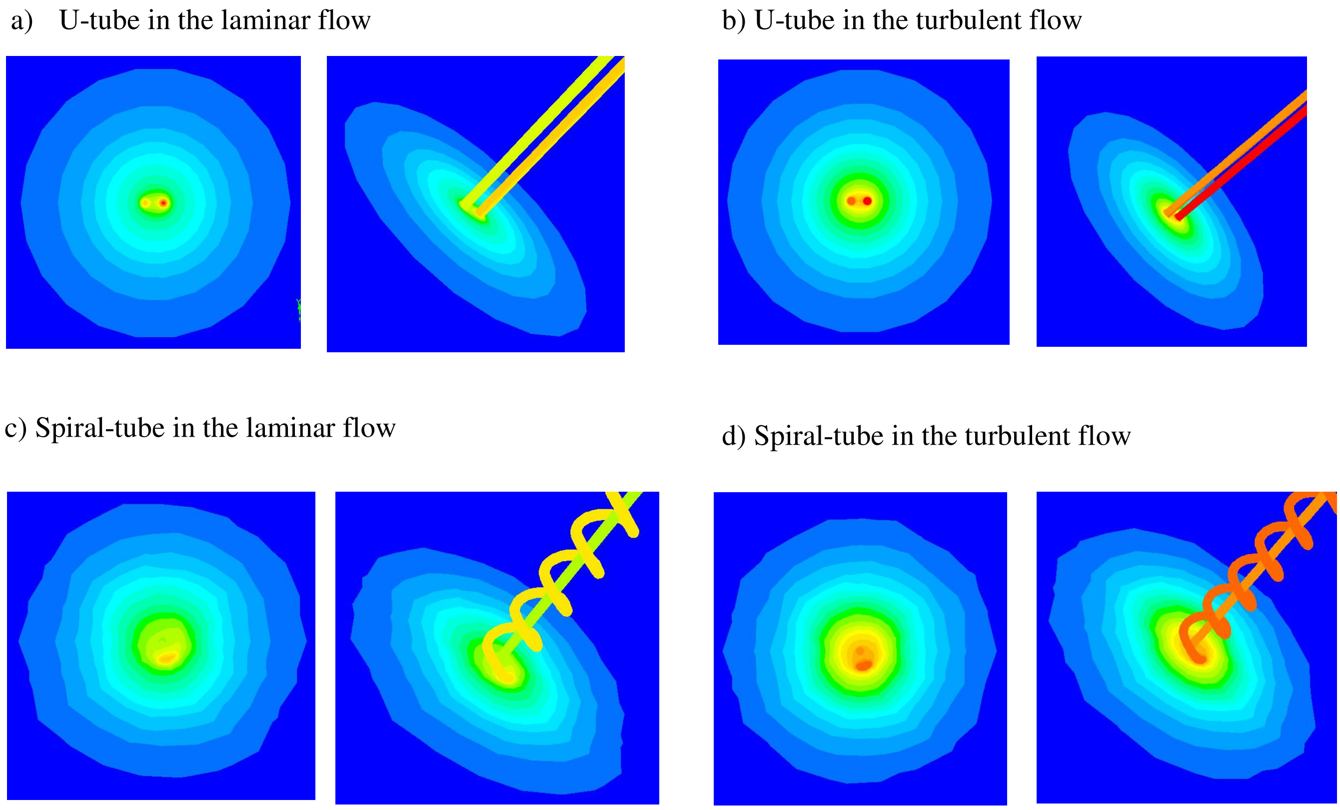


Fig. 8 Temperature contours of the U-tube and Spiral-tube GHEs with borehole backfilled with silica sand in the laminar & turbulent flows

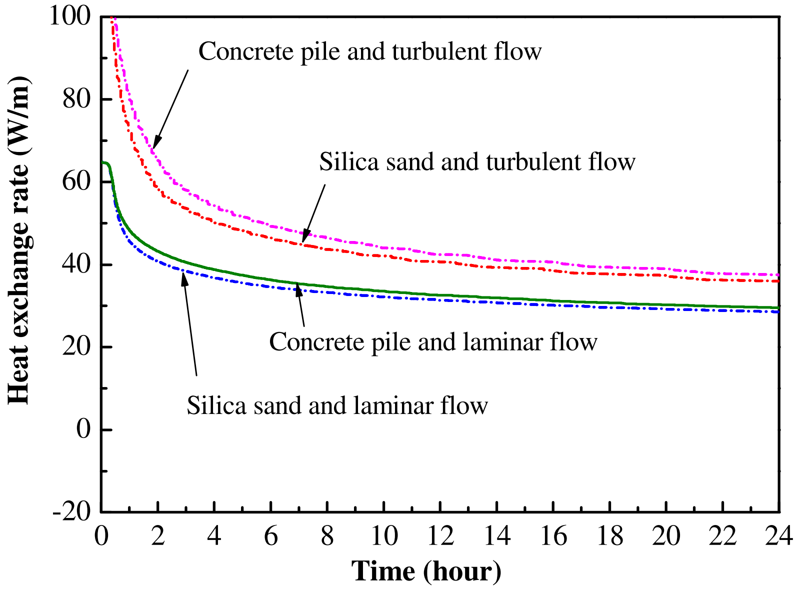


Fig. 9 Heat exchange rate of spiral-tube GHEs with different backfilled materials, silica sand and concrete pile

The models of the spiral tube GHEs installed in a concrete pile were also simulated in the laminar and turbulent flows. Heat exchange rates of the spiral tube GHEs with different backfilled materials, silica sand and concrete pile are shown in Fig. 9. The heat exchange rate of the spiral-tube GHE installed in a concrete pile shows a slightly better performance of 5 % in the laminar flow and 6 % in the turbulent flow compared with the spiral-tube backfilled with silica sand. This is due to the higher thermal conductivity of the concrete pile than that of silica sand.

Table 4 shows the heat exchange rates of the U-Tube and spiral-tube GHEs with different backfilled materials, silica sand and concrete pile.

Table 4 Heat exchange rates of the U-Tube and Spiral-tube GHEs

GHEs Types	Heat exchange rate (W/m) (*Average in 24 h operation*)
a) U-Tube GHE	
Grout (material: Silica sand)	
Laminar flow (2 l/min)	20.1
Turbulent flow (8 l/min)	32.5
b) Spiral-Tube GHE	
Grout (material: Silica sand)	
Laminar flow (2 l/min)	32.7
Turbulent flow (8 l/min)	43.4
Concrete pile	
Laminar flow (2 l/min)	34.2
Turbulent flow (8 l/min)	46.2

4.2 Heat Exchange Rates and Characteristics of Spiral-Tube GHEs

The performances and characteristics of the spiral-tube GHE are investigated by simulating the GHE models in various conditions with varying spiral pitches of p = 0.05 m; 0.1 m and 0.2 m and outlet pipe positions.

4.2.1 Different Pitches

Different pitches for the spiral-tube GHEs with outlet pipe installed inside are p = 0.05 m; 0.1 m and 0.2 m. The spiral-tube GHE models are simulated in the laminar and turbulent flows for each pitch. Heat exchange rate of the spiral-tube GHEs with pitches of p = 0.05; 0.1; and 0.2 m are shown in Fig. 10. Increasing the spiral pitch reduces the number of spirals per meter borehole depth and reduces the heat exchange rate of the GHE. Temperature contours of the spiral-tube with p=0.05; 0.1 & 0.2 m in the laminar & turbulent flows respectively can be seen in Fig. 11.

4.2.2 Outlet Tube Positions

The spiral-tube GHE model with outlet tube installed outside the spiral tube was also simulated. Fig. 12 shows the heat exchange rates of the spiral-tube GHEs with different outlet tube positions. The heat exchange rate of the GHE with outlet tube installed outside increases by 2 % in the laminar flow and 10 % in the turbulent flow compared to that of the outlet tube installed inside the spiral tube. Operating this GHE in the turbulent flow gives a better performance than that of the laminar flow. Thermal interferences between the down and up pipes affect its performance as can be seen in its water temperature distribution through the depth for the down and up pipes as shown in Fig. 13. Fig. 14 shows the temperature contours of the spiral-tube GHEs with outlet tube installed outside in the laminar and turbulent flows.

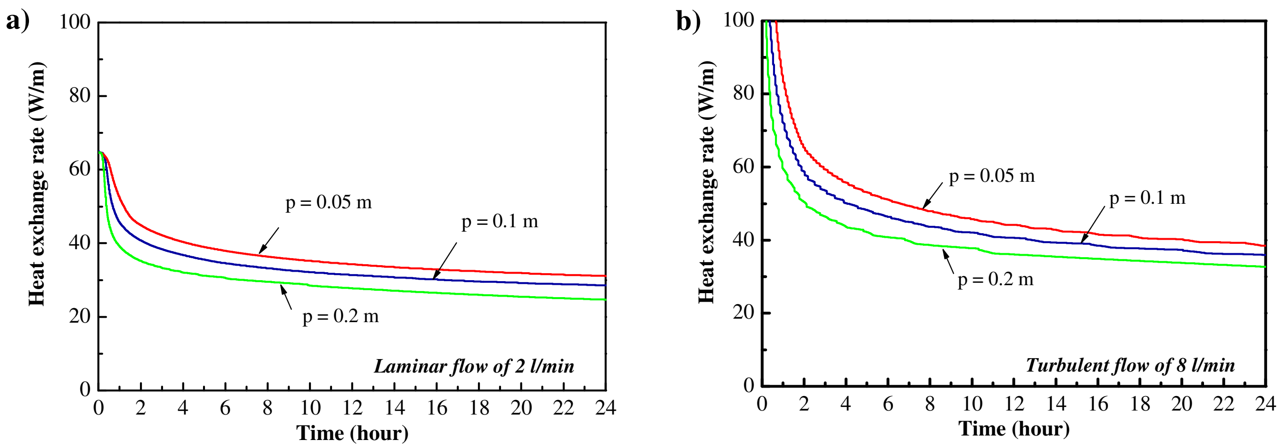


Fig. 10 Heat exchange rate of spiral-tube GHEs with various pitches of p = 0.05; 0.1; and 0.2 m

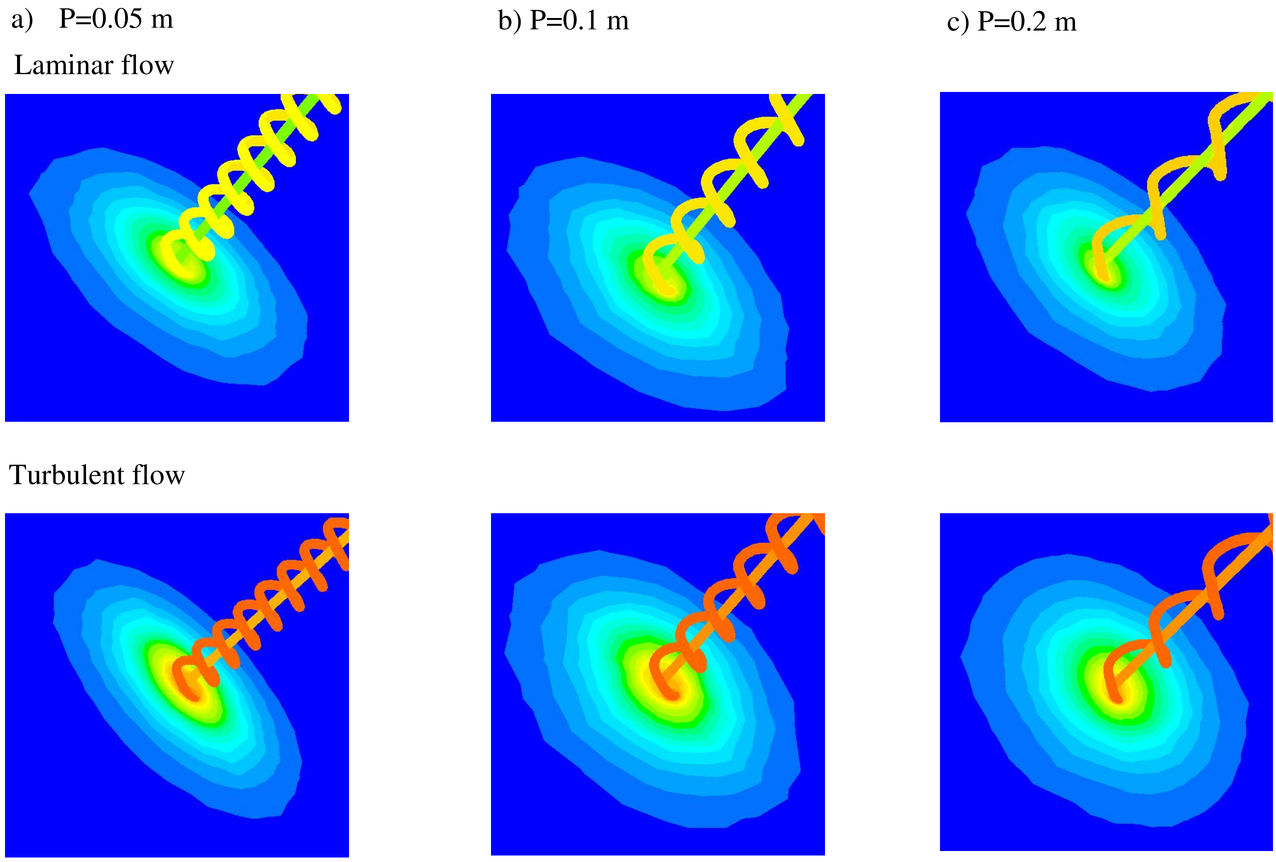


Fig. 11 Temperature contours of Spiral-tube with p=0.05; 0.1 & 0.2 m in the laminar & turbulent flows

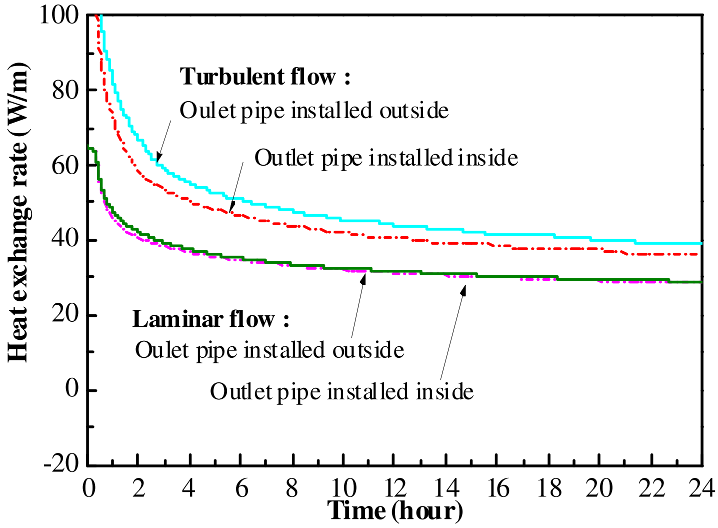


Fig. 12 Heat exchange rate of spiral-tube GHEs with different outlet tube positions

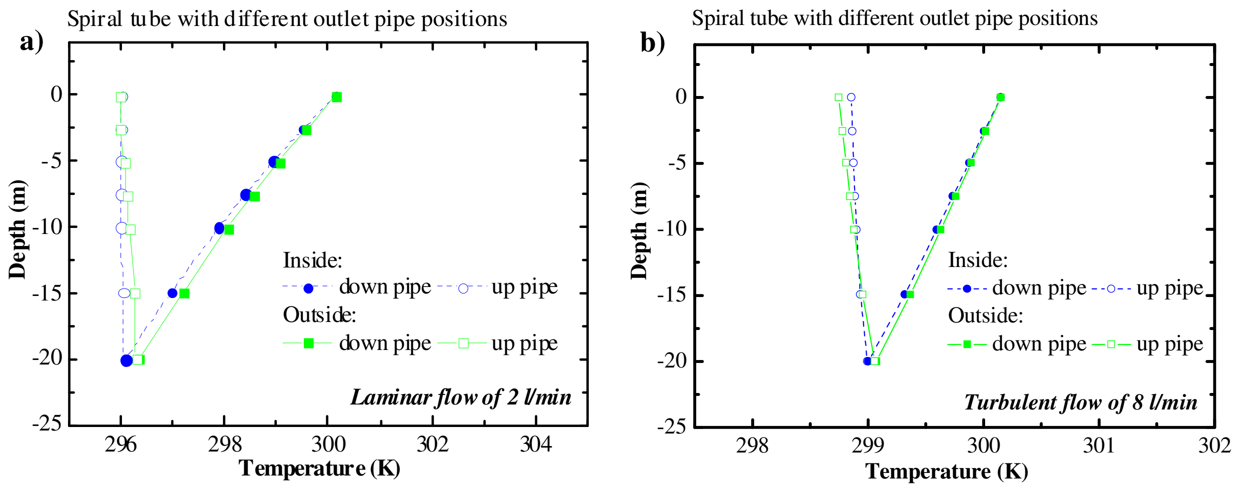


Fig. 13 Water temperature distribution of the GHEs after 24 h operation

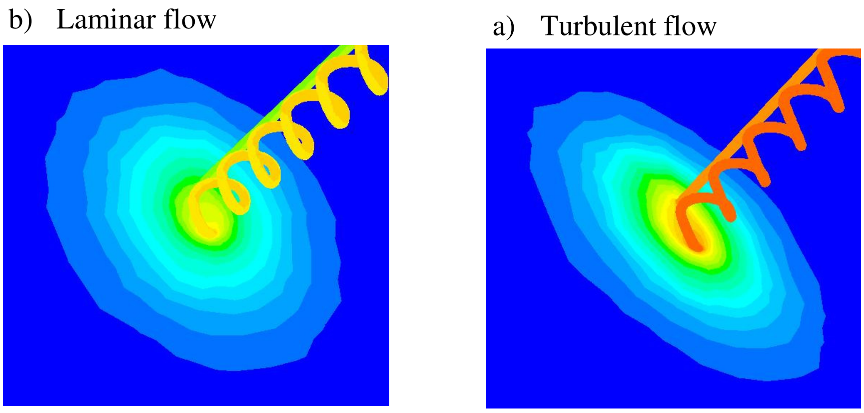


Fig. 14 Temperature contours of the spiral-tube GHEs with outlet tube installed outside

Finally, the performances and characteristics of the spiral-tube GHE in various conditions including varying spiral pitches of p = 0.05 m; 0.1 m and 0.2 m and outlet tube positions are compared. Fig. 15 shows the heat exchange rates of the GHEs in the various conditions. Average heat exchange rates in 24 h operation of the GHEs with various conditions including U-tube, varying spiral pitches and outlet positions of the spiral-tube GHEs respectively are presented in Table 5.

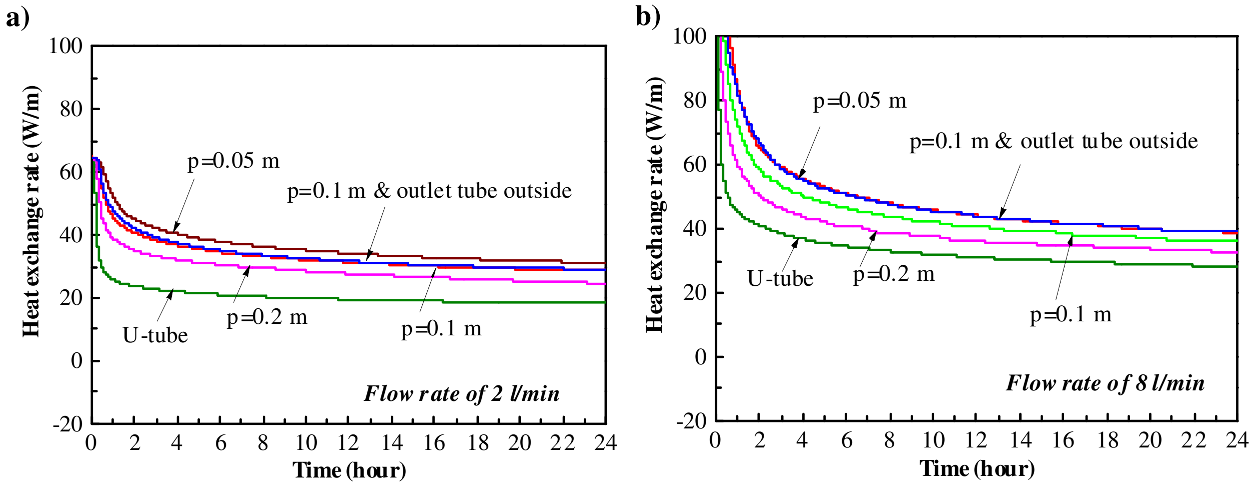


Fig. 15 Heat exchange rates of the GHEs in the various conditions

Table 5 Average heat exchange rates of the GHEs in various conditions

Spiral-Tube GHEs	Heat exchange rate (W/m) (*Average in 24 h operation*)
U-Tube GHE	
Laminar flow (2 l/min)	20.1
Turbulent flow (8 l/min)	32.5
Spiral-Tube GHE	
a) p = 0.05 m	
Laminar flow (2 l/min)	35.9
Turbulent flow (8 l/min)	47.7
c) p = 0.1 m	
Laminar flow (2 l/min)	32.7
Turbulent flow (8 l/min)	43.4
c) p = 0.2 m	
Laminar flow (2 l/min)	28.7
Turbulent flow (8 l/min)	38.6
c) Outlet pipe outside	
Laminar flow (2 l/min)	33.3
Turbulent flow (8 l/min)	47.6

6. CONCLUSIONS

Thermal performance and characteristics of spiral-tube ground heat exchanger (GHE) for ground source heat pump in the laminar and turbulent flows are investigated. Three-dimensional unsteady-state models were built and simulated using the CFD-code, FLUENT in order to investigate heat exchange from the GHEs system to the ground around the borehole. From the simulation results, the following conclusions could be drawn:

1. The performance of spiral-tube GHE increases by 62.7 % in the laminar flow and by 33.5 % in the turbulent flow compared with the conventional U-tube GHE. This provides the possibility for reducing the borehole depth of the GHE. Reducing the borehole depth is attractive economically due to reducing installation cost.
2. The performance of the spiral-tube GHE installed in a concrete foundation pile shows a slightly better performance, of 5 % in the laminar flow and 6 % in the turbulent flow, compared with the spiral-tube backfilled with silica sand. Installing the GHE in the concrete foundation piles can reduce installation cost.
3. Increasing the spiral pitch reduces the number of spirals per meter borehole depth and as a result reduces the heat exchange rate of the GHE.
4. Operating the spiral-tube with outlet tube installed outside compared with that inside is better in the turbulent flow than that of in the laminar flow.

NOMENCLATURE

m	mass flow rate	(kg s^{-1})
c_p	specific heat	(J kg^{-1} K^{-1})
T	temperature	(K)
Q	heat exchange rate	(W)
L	borehole depth	(m)
$\overline{Q}$	heat exchange rate per unit length	(Wm^{-1})
k	thermal conductivity	(Wm^{-1}K)
ρ	density	(kgm^{-3})
x	leg spacing	(m)
p	pitch	(m)

Subscript

o	outer
i	inner
PE	Polyethylene

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